

Using the Frye SPL Fitting Software to Fit Hearing Aids Incorporating Nonlinear Signal Processing

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INTRODUCTION

With the increasing use of hearing aids with nonlinear signal processing (Kirkwood, 1996; Fabry, 1993) and the routine use of probe microphone technology in the fitting and verification process, a serious "prescriptive test-gap" has become increasingly evident. This "prescriptive test-gap" primarily exists because the popular prescriptive insertion gain approaches like Berger (Berger et al, 1989), NAL-R (Byrne and Dillon, 1986, Libby 1/3-1/2 (Libby, 1986), and Prescription of Gain/Output (POGO) (McCandless and Lyregard, 1983), which have been used with probe microphone systems for over ten years, were all designed or based around the use of hearing aids using linear signal processing (Neuman et al, 1995).

Because many dispensers are using more hearing aids with nonlinear signal processing, this "prescriptive test-gap" has become a very important issue among dispensers. Of course, because of Frye Electronics' position in the marketplace, dispensers often ask, "What prescriptive approach should be used to fit hearing aids with nonlinear signal processing?" This same question is being asked and is trying to be addressed by other instrumentation manufacturers as well. Some of these include the Madsen Aurical, Etymonic Designs' Audioscan and ReSound's Real Ear Loudness Mapping (RELM). This same problem is also a major topic at lectures, conventions, and appears in many of the professional journals (Mueller, 1997; deJonge, 1996).

RECENT APPROACHES TO FIT HEARING AIDS WITH NONLINEAR SIGNAL PROCESSING

A. The IHAFF Protocol

One of the first approaches came from the Independent Hearing Aid Fitting Forum (Valente and Van Vliet, 1997; deJonge, 1996; Van Vliet, 1995), a working group of twelve audiologists. The IHAFF approach has three major components: 1) The Contour Test - a loudness growth test. 2) Abbreviated Profile of Hearing Aid Benefit (APHAB) a question and answer format to evaluate a patient's perceived benefit with the hearing aid(s), and 3) Visual Input/Output Algorithm (VIOLA) which is an input/output procedure to help select and verify the compression characteristics of nonlinear hearing aids at usually two frequencies (i.e., 500 Hz and 3000 Hz) in an effort to provide adequate amplification across a wide range of input levels. One of the goals of this approach is to assure that the selected hearing aid(s) has the capability of making "soft" (i.e., 50 dB SPL) sounds audible; "average" (i.e., 65 dB SPL) sounds comfortable while making sure "loud" (i.e., 80 dB SPL) sounds are not uncomfortably loud.

B. FIG6

Mead Killion of Etymotic Research has recently introduced a software program called FIG6, (FIG6, 1996; deJonge, 1996). This approach provides dispensers with the ability to develop and display on a computer program - three different insertion gain targets for three different test signal input intensities. The FIG6 approach uses input levels of 45, 65 and 95 dB lSPL to assess the performance of the nonlinear signal processing of the hearing aid(s). FIG6 also can calculate and display the 2cc full-on coupler gain for BTE, ITE, ITC or CIC hearing aids which is helpful to use when ordering or selecting hearing aids that will "hit" the prescribed real ear insertion response (REIR). What makes FIG6 different from the IHAFF approach is that FIG6 predicts the loudness discomfort level (LDL) from thresholds and IHAFF requires individual measurement of loudness growth.

C. **DSL and DSL [i/o]**
The third fitting method is the DSL software which was developed by Dr. Richard Seewald and associates at the University of Western Ontario, (Seewald et al, 1993). Two of the major innovations of the DSL approach are: 1) The use of the patients' Real Ear to Coupler Difference (RECD) to calculate the patient's desired gain and SSPL90 targets, and 2) the display of the patient's dynamic range of a SPL-O-Gram format. Recently, the DSL [i/o] approach has been introduced which includes the use of multiple targets for varying input levels and allows for the selection of a hearing aids compression characteristics (Cornelisse et al, 1995; Seewald et al, 1995).

Even though these new approaches are designed to help the dispenser do a better job of fitting current hearing aids incorporating nonlinear amplification there are a few very important facts that must be understood. With the exception of DSL, none of these fitting approaches (IHAFF, FIG6, DSL [i/o] or Frye/SPL) have been validated. That is, the efficacy (validity) of these procedures have not been tested on a large number of subjects and the results reported in peer reviewed journals. Until such group testing and peer reviews validate these procedures, it is unknown, at this time, if implementation of any or all of these procedures will result in a hearing aid fitting which is any better or worse than any other currently used procedure. It is also important to note that sometimes new approaches can answer one question while at the same time creating a new set of problems. For example, two out of three of these approaches require the use of a computer. The exception is DSL, which is available on the Audioscan and DSL(i/o) which will soon be available on the FONIX FP40 series. As is well known, the need to have and operate a computer can create a new set of problems.

First, computers and even the "simplest" software can be very time consuming to learn. For the busy practitioner, this could create a problem. Second, even though these software programs are available either free, i.e., IHAFF and FIG6 or like DSL[i/o] very inexpensive, it may be necessary to buy a new computer to run these programs. The cost of a computer, monitor and printer can range from approximately $2000 to $5000. In smaller offices, there could be problems associated with the physical space an extra computer would require. Finally, even though as a hearing aid dispenser it is becoming increasingly more necessary to operate a computer, there are many dispensers who are still quite computer phobic or illiterate (Ketchum, 1997).

FRYE/SPL FITTING TEST

Frye Electronics has developed a simple test procedure taking advantage of some of the common points and unique benefits provided by the IHAFF, FIG6, DSL and DSL[i/o] approaches. In general, these three approaches have the following important points in common with the Frye/SPL approach. 1) The ability to convert audiometric data (dB HL) into output (dB SPL) and display this data in a dynamic range (DR) format, similar to the DSL SPL-O-gram, 2) Like FIG6 (except as REAR's), it provides multiple targets for multiple input levels rather than a single real ear insertion response (REIR) prescriptive target as is commonplace for hearing aids with linear signal processing, 3) The capability to use more than one input level and signal type. Frye also wanted to accomplish the development of a useful test procedure without the need for the dispenser to buy an additional test instrument or a computer. With thousands of FONIX analyzers in use worldwide, it is very important to Frye to be able to offer a new test at an economical price. Also, Frye wanted to provide dispensers with a new test procedure that would be fast and easy to use in their practice. Frye believes that the probe microphone "Frye/SPL Test" approach meets all the development goals and helps fill the "prescriptive testing-gap"!

The following is an overview of how the Frye/SPL test approach operates. The following section also provides examples of the various test screens from a FONIX 6500-CX Real Time Hearing Aid Test System software version 4.20. The same Frye/SPL test procedure is also available on the FONIX FP40 Portable and FP40-D Desktop hearing aid and probe microphone analyzers with version 3.30 software. Early models of both the 6500 and FP40 series can be upgraded to add the new Frye/SPL test.

All of the following Frye/SPL audiometric information is entered by using the 6500-CX Quik-Probe II hand held remote module. The required patient audiometric data can be entered and the SPL test procedure can be implemented prior to the patient's scheduled fitting appointment.

Entering Audiometric Data

After entering the Quik-Probe II main menu, the "SPL Target" mode must be selected from the "Create Target" choices by pressing the < or > arrows on the handheld remote, as shown in (Figure 1). Next, the dispenser enters the "SPL Setup Menu" by pressing the menu key and selects, a) the test ear, b) the most comfortable loudness level (MCL) target based on NAL-2, POGO, Berger, or 1/3-1/2-2/3 gain formulas, c) finally, the user must decide whether measured or predicted values will be used for UCL (uncomfortable loudness levels) target values (Figure 2). After exiting the "SPL Setup Menu", the patient's audiometric (in dB HL) and UCL (in dB HL) thresholds are entered for each test frequency (250 to 8000 Hz in octave and mid-octave steps) on two separate screens. At the present time, thresholds and UCL can only be entered in dB HL. These values cannot be entered in dB SPL. Figures 3 and 4 respectively, are examples of the HTL and UCL entry screens. However, if predicted UCL values in Table 4, (Pascoe, 1988) have been selected in the "SPL Setup Menu" and are used instead of measured UCL values, the UCL data entry screen can be bypassed and the user goes directly to the "Main SPL Test" screen (Figure 5). When the user goes to the "Main SPL Test" screen, the entered HL data will automatically be converted by the FONIX 6500-CX software into a dB SPL format. ANSI S3.6-1989 is used for HL to SPL conversions (Table 4). As with any new and invalidated fitting approach, Frye Electronics based on feedback from users or for other reasons, expects it may be making some modifications and changes to its SPL Fitting approach in the future.

On the main SPL test screen (Figure 5) the converted HL threshold data will appear as a capital "T" at each entered frequency (ANSI 3.6-1989). The MCL target is the double thick (-) line. This target is based on one of the insertion gain targets available from the "SPL Setup Menus". So that there is no misunderstanding, the MCL target, as used here, should be considered a most comfortable level target because the target is based on: 1) a linear insertion gain (REIG) target formula, 2) an average conversation test signal input of 60-70 dB SPL, 3) the general belief that a REIG target is basically a MCL target. In this case the NAL-2 target (see Figure 2) was used, and was modified and speech-weighted (Figure 6, Tables 1,2,3) resulting in the double thick lined curve seen in Figure 5. Frye believes this modified target better approximates a real-world MCL target. Because this MCL target curve has been modified by using a speech-weighted factor, it rolls off in the higher frequencies. Therefore, the MCL target will in some cases be at or below the displayed thresholds ("T"). The final data that ap-

QUIK-PROBE II MENU	
CREATE TARGET	SPL TARGET
MODE	COMP/AUTO
OPERATION PARAM	
GAIN(G)/SPL	SPL
AVERAGE UNAIDED	
CALIBRATE PROBE	
EAR TESTED	RIGHT
MULTICURVE	

Figure 1. Fonix 6500-CX Quik-Probe 11 Menu

SPL SETUP MENU	
EAR TESTED	RIGHT
FORMULA	NAL-2
PREDICT UCL	YES

Figure 2. SPL setup menu

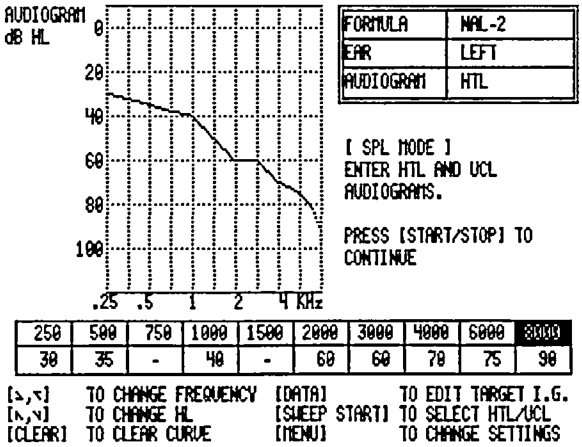


Figure 3. HTL audiogram

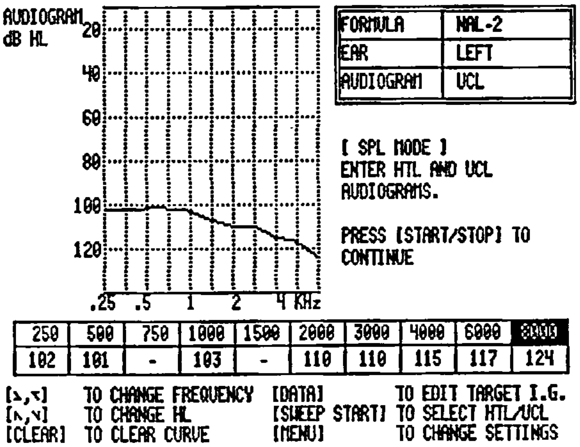


Figure 4. UCL audiogram

pears on the graph of the main test screen is an upper case "U" which represents the measured or predicted UCL targets.

To save time, all HL entries (T, U and MCL targets) can be made prior to the patient arriving for the fitting. Frye made every effort to help guide users through the various step-by-step entries. This task is accomplished with the use of numerous on-screen user "help messages". Examples of these help messages appear on the lower right portion of the main screen (Figures 4 and 5). The key to using these "help messages" is simple - any capitalized word either in brackets, i.e. [MENU] TO CHANGE SETTINGS (Figure 3), or a single capitalized word followed by a blank space is the instrument button to be pressed to complete the action statement that follows. In Figure 5, an example of this type of help message

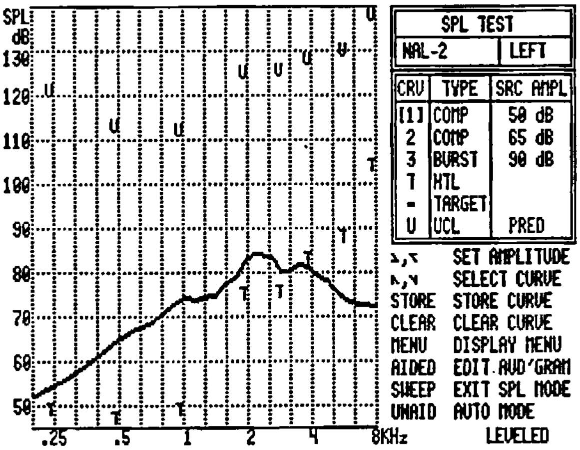


Figure 5. Main SPL test screen

The Target IG is converted to the Target SPL

1. Add the source level for Aided curve 2.
2. Interpolate from 10 frequency to 80 frequency curve frame.
3. Add the AVG Unaided ear response REUR in Table 1.
4. If Aided 2 is composite, subtract 10.7 dB from each frequency. If Aided 2 is Speech Weighted tone, add 2.1 dB to each frequency.
5. If Aided 2 is Speech Weighted, subtract the Speech Weighting in Table 2.

The complete formula is then:

Target SPL = Target IG + CRV2 source + AVG REUR
(If Aided2 is composite) - 10.7 dB - Speech Weighting.
(If Aided2 is speech tone) + 2.1 dB - Speech Weighting.

Figure 6. Target IG to target SPL conversion formula

is; CLEAR (space) CLEAR CURVE. These help messages indicate or direct the user to push the labeled button on the control module to complete the action statement or task that immediately follows.

Now, with the patient's threshold (T), the MCL target (-), and uncomfortable threshold (U) displayed the dispenser has two very useful pieces of test data displayed. First, the dispenser has three targets predicted in dB SPL near the eardrum. In addition and most importantly, the dispenser has the patient's audiometric residual dynamic range (DR) displayed on the screen!

FRYE/SPL TEST

In Figure 7, the SPL TEST status window indicates:

a. The MCL target is based upon the NAL-2 prescriptive target
b. The test ear is the left ear
c. Curve #1 (CRV column) was generated using a 50 dB composite signal
d. Curve #2 was generated using a 65 dB composite signal
e. Curve #3 was generated using a 90 dB burst (explained later)
f. T is the threshold target based on the entered audiogram
g. (-) is the MCL target based on the NAL-2 prescriptive formula
h. U is the UCL target, in this case, predicted from the audiogram

For curves 1 and 2, a 50 dB and 65 dB composite signal are the defaults. Frye believes this broadband speech-weighted composite noise is one of the most realistic signals available for testing nonlinear hearing aids. In support of this belief there is an optional hearing aid testing stan-

Table 1. Average real-ear unaided response (REUR).

Freq (Hz)	Gain dB	Freq (Hz)	Gain dB	Freq (Hz)	Gain dB	Freq (Hz)	Gain dB
		2100	13.9	4100	12.7	6100	7.7
200	1.6	2200	14.7	4200	12.4	6200	7.5
300	2.1	2300	15.1	4300	12.2	6300	7.3
400	.7	2400	15.0	4400	12.0	6400	7.2
500	2.9	2500	15.1	4500	11.9	6500	7.1
600	2.9	2600	15.0	4600	11.7	6600	6.9
700	3.1	2700	14.6	4700	11.6	6700	6.8
800	3.3	2800	14.1	4800	11.2	6800	6.6
900	3.6	2900	13.6	4900	10.7	6900	6.5
1000	3.4	3000	13.7	5000	10.3	7000	6.4
1100	3.1	3100	13.8	5100	9.9	7100	6.2
1200	3.6	3200	14.1	5200	9.5	7200	6.1
1300	4.2	3300	14.5	5300	9.2	7300	6.0
1400	4.4	3400	14.8	5400	8.9	7400	5.7
1500	5.6	3500	14.9	5500	8.7	7500	5.4
1600	7.0	3600	14.7	5600	8.5	7600	5.1
1700	8.1	3700	14.3	5700	8.3	7700	4.8
1800	9.3	3800	13.9	5800	8.2	7800	4.6
1900	10.9	3900	13.5	5900	8.0	7900	4.4
2000	12.6	4000	13.1	6000	7.8	8000	4.2

dard (ANSI 3.42-1992) that recommends using a broadband signal as an alternative to pure-tones for "assessing the performance of hearing aids in environments more nearly representing their real-world use." A static example of the Frye real-time composite signal frequency spectrum is shown in Figure 8. In current software versions the real-time composite signal can test the complete frequency response (200-8000 Hz) up to 8 times a second. For curve 3, Frye developed a new one-second short burst pure-tone sweep signal for evaluating the output of the hearing aid to a 90dB SPL input. This short burst signal is presented at each one of the ten standard audiometric frequencies from 250 Hz to 8000 Hz. It is desired that the measured output for the 90 dB SPL burst signal is below the "U" target curve. In this instance, Frye recommends using a pure-tone to measure maximum output rather than the composite signal because a pure-tone output is frequency-specific as compared to the total RMS output of a composite test signal. Earlier Frye and other analyzers currently available use a several second long loud signal, this new very short one second 90dB SPL saturation test is much more patient friendly. Of course, when desired or necessary, the dispenser can change any of these defaults and select input levels from 40dB to 90dB SPL in 5 dB steps by using the arrow buttons. In addition, the dispenser can change the default signal. Finally, all the user help messages, status of the sound field calibration (i.e., LEVELED or UNLEVELED), test date and time are displayed directly below the SPL Test status window (Figure 5).

Table 2. Speech weighting.

Freq (Hz)	Gain dB	Freq (Hz)	Gain dB	Freq (Hz)	Gain dB	Freq (Hz)	Gain dB
		2100	8.1	4100	13.4	6100	16.7
200	0.2	2200	8.4	4200	13.6	6200	16.9
300	0.5	2300	8.8	4300	13.8	6300	17.0
400	0.8	2400	9.1	4400	14.0	6400	17.1
500	1.2	2500	9.4	4500	14.1	6500	17.3
600	1.6	2600	9.7	4600	14.3	6600	17.4
700	2.1	2700	10.0	4700	14.5	6700	17.5
800	2.5	2800	10.3	4800	14.7	6800	17.6
900	3.0	2900	10.6	4900	14.9	6900	17.8
1000	3.5	3000	10.8	5000	15.0	7000	17.9
1100	4.0	3100	11.1	5100	15.2	7100	18.0
1200	4.4	3200	11.3	5200	15.4	7200	18.1
1300	4.9	3300	11.6	5300	15.5	7300	18.2
1400	5.3	3400	11.8	5400	15.7	7400	18.4
1500	5.8	3500	12.1	5500	15.8	7500	18.5
1600	6.2	3600	12.3	5600	16.0	7600	18.6
1700	6.6	3700	12.5	5700	16.1	7700	18.7
1800	7.0	3800	12.7	5800	16.3	7800	18.8
1900	7.4	3900	13.0	5900	16.4	7900	18.9
2000	7.7	4000	13.2	6000	16.6	8000	19.0

Automatic or Manual Mode

Two SPL Test modes are available. Users may chose either the "automatic" or "manual" mode. The default signal types (composite and pure-tone burst) and input levels (50 dB, 65 dB and 90 dB SPL) are the same in either test mode. In the automatic mode, the software automatically advances from Curve 1 through Curve 3 when the dispenser presses the "Stat/Stop" button on the remote module or the footswitch. In the manual mode, the dispenser must use the "Up/Down" arrow buttons on the remote to select the curves to be tested. Also, the dispenser can change Curve 1-3 input levels with the <,> arrow keys and the signal type by pressing the Menu button (Figure 9). This gives the dispenser greater control to test and re-test the same curve until a certain desired test result is achieved. In either mode, because of the real-time composite signal or the new short burst pure-tone sweep, it takes only a few seconds to complete a test curve and just a few minutes to complete the entire test.

Probably one of the biggest differences between the Frye/SPL test and a traditional insertion gain (REIG) test is that a real ear unaided response (REUR) is not measured. Test curves 1 through 3 are all performed as real ear aided responses (REAR). With the Frye/SPL test, the dispenser is interested in determining the output (in dB SPL measured near the tympanic membrane) instead of the gain of the hearing aid. In addition, the dispenser is determining how the output "fits" within the dynamic range of the ear (threshold to UCL) instead of determining how close the measured gain is to a prescribed REIR target.

Table 3. HL to SPL (or SPL to HL) conversion table from ANSI S3.6-1989 Table G.1.

Freq (Hz)	dB
250	19.0
500	12.0
750	10.5
1000	9.0
1500	12.0
2000	15.0
3000	15.5
4000	13.0
6000	13.0
8000	14.0

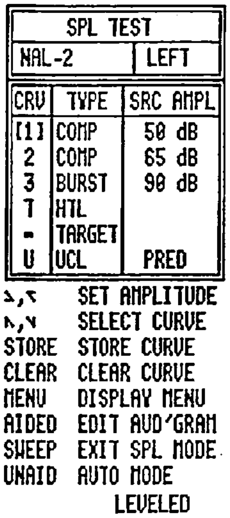


Figure 7. SPL Test status window

Performing the SPL/TEST

The first measurement is CRV [1]. In Figure 10a, a 50dB SPL composite signal is used to measure the performance of the hearing aid and the result is stored as Curve 1. The objective is to determine if the measured output exceeds the patient's threshold (T). If so, the dispenser can safely assume that "soft" sounds are audible. The assumption of audibility is somewhat similar in concept to the audibility index (AI) approach which is also a threshold-based measure of audibility.

The next measurement is CRV [2]. The measured output for the 65 dB SPL composite signal should approach the MCL target curve as shown in (Figure 10b). If it is, the goal of making average conversational speech "comfortable" will have been achieved. It is important that the dispenser should think of this prescriptive MCL target as a guide, not an absolute. Prescriptive targets are not intended to replace the communication between the dispenser and the patient during the fitting process.

To complete the Frye/SPL test sequence, CRV [3] uses a 90dB short burst (one second) pure-tone sweep to measure the output as compared to

Table 4. HTL (HL) to UCL (HL) prediction table from Pascoe(1988) Table 4.

HTL dBHL	UCL HL	HTL dBHL	UCL HL
0	97	65	114
5	99	70	115
10	99	75	117
15	98	80	120
20	97	85	120
25	101	90	124
30	102	95	130
35	101	100	127
40	103	105	133
45	105	110	134
50	107	115	137
55	108	120	140
60	110		

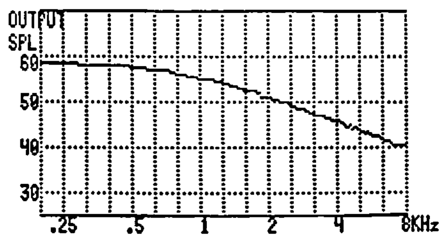


Figure 8. Frye speech-weighted composite signal

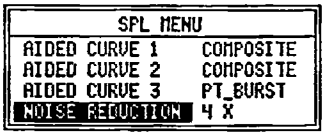


Figure 9. SPL menu

the patient's uncomfortable values. In the upper part of the SPL graph in Figure 10c, the CRV [3] measurements are displayed relative to the UCL (U) target. Each numeral #3 is positioned on the graph at one of the ten standard audiometric frequencies.

CASE STUDIES

The following case studies were performed using a FONIX FP40 Hearing Aid Analyzer with Probe Option with beta Frye/SPL software (Personal Communication, J. Knapp). In both cases, the fittings were considered successful based on the objective test results provided by the Frye/SPL fitting approach and the affirmative subjective response of each patient. As mentioned earlier, the SPL test approach is the same for the FP40 and 6500-CX.

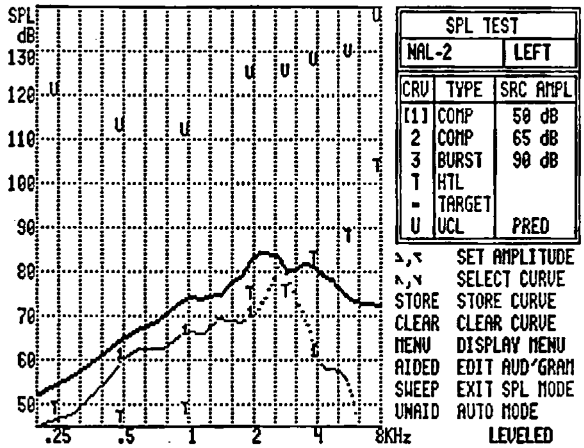
A. Patient 1: (Figures 11a and 11b)

This patient is a 60-year-old female with previous hearing aid experience. Based on the audiometric examination and the dispenser's experience, a completely in the canal (CIC) programmable hearing aid using wide dynamic range compression (WDRC) signal processing was chosen. Upon completion of the initial SPL test (Figure 11a), the hearing aid settings demonstrated an acceptable frequency response "shape" and 90 dB real ear saturation response ($RESR_{90}$). But, it was thought that the 50 dB SPL and 65 SPL response curves outputs could be improved. This is especially true for the 65 dB SPL input curve because it fell significantly below the MCL target. As Figure 11B demonstrates, both the 50 and 65 dB SPL input curves showed significant improvement as the 65 dB SPL response (Curve 2) very closely matches the MCL target.

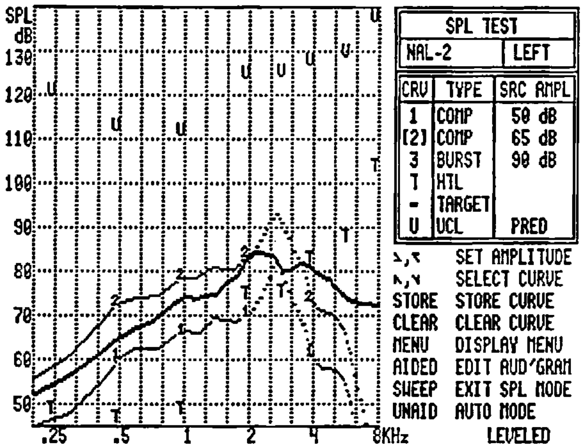
B. Patient 2: (Figures 12a and 12b)

This patient is a 14-year-old male with previous hearing aid experience. In this case, the patient was fitted with a programmable ITC hearing aid incorporating wide dynamic range compression. The initial SPL test (Figure 12a) illustrates that

A



B



C

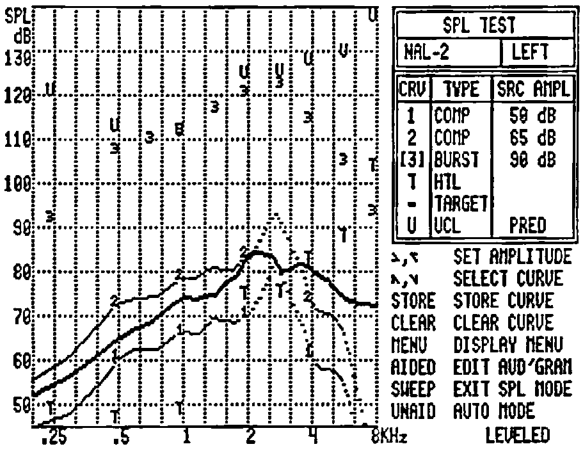
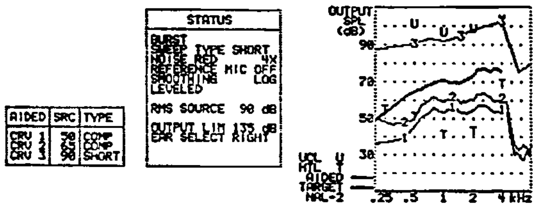


Figure 10a. SPL Test, CRV [1], 50 dB SPL composite Input

Figure 10b. SPL Test, CRV [2], 65 dB SPL composite Input

Figure 10c. SPL Test, CRV [3], 90 dB SPL short burst



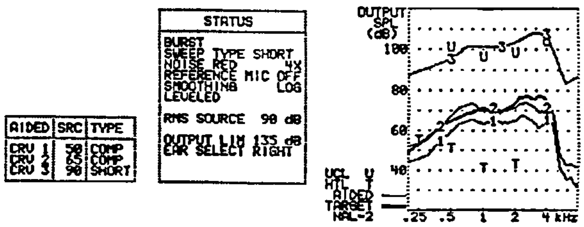
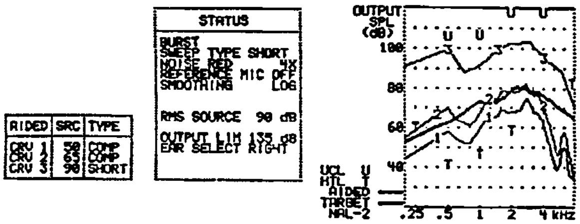


Figure 11a. Patient 1: WDRC - Programmable Instrument
Pre-Adjust: 1. Unacceptable response for 50 and 65 dB SPL inputs.
2. RESR-90 acceptable.
3. Frequency response acceptable.

Figure 11b. Patient 1: WDRC - Programmable Instrument.
Post-Adjust: 1. Improved response for 50 and 65 dB SPL inputs.



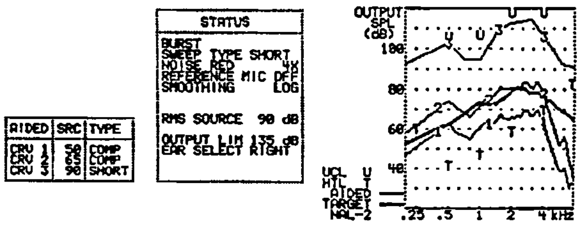


Figure 12a. Patient 2: WDRC Two Channel/Multi-memory Instrument.
Pre-Adjust: 1. Acceptable 50 and 60 dB SPL target correlation.
2. RESR-90 to low.

Figure 12b. Patient 2: WDRC Two Channel Multi-memory Instrument.
Post-Adjust: 1. Improved RESR-90.

the frequency response for both the 50 and 65 dB SPL inputs approach their respective "T" and MCL targets, but the $RESR_{90}$ was significantly below the "U" target. After adjustments were made to the compression kneepoint and compression ratio, the measured $RESR_{90}$ was increased to just below the UCL levels making full use of the patient's residual dynamic range (Figure 12b).

SUMMARY

There is no doubt that the hearing healthcare profession is at the dawn of an exciting new era in the advancement of hearing aid technology. Within the last few years there has been a major shift from dispensing linear hearing aid technology into a new era of so many unique hearing aid circuit choices. Today there are so many choices, from improved and more sophisticated linear circuits, i.e., class D amplifiers, to almost completely adjustable nonlinear analog and most recently fully digital circuits! Keeping current with today's hearing aid technology challenges even the most dedicated hearing healthcare professional.

.In fact, the idea of keeping current is what best summarizes the primary focus of this manuscript. At Frye Electronics, we are continually striving to find better, easier and more helpful methods of evaluating the electroacoustic performance of a hearing aid. An example of this commitment is the experimental "digital speech" software approach for evaluating the performance of the new digital signal processing hearing aids that we demonstrated at this year's American Academy of Audiology convention. We believe that the new Frye/SPL fitting test will help dispensers keep up with today's new technology by providing hearing healthcare professionals with an important next step that is both a practical and easy-to-use fitting approach for utilization with all types of hearing aids.

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